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A search for high-mass resonances decaying to $\tau^+\tau^-$ in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

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ABSTRACT

This Letter presents a search for high-mass resonances decaying into $\tau^+\tau^-$ final states using proton–proton collisions at $\sqrt{s} = 7$ TeV produced by the Large Hadron Collider. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 4.6 fb^{-1}. No statistically significant excess above the Standard Model expectation is observed; 95% credibility upper limits are set on the cross section times branching fraction of Z' resonances decaying into $\tau^+\tau^-$ pairs as a function of the resonance mass. As a result, Z' bosons of the Sequential Standard Model with masses less than 1.40 TeV are excluded at 95% credibility.

1. Introduction

Many extensions of the Standard Model (SM), motivated by grand unification, predict additional heavy gauge bosons [1–6]. As lepton universality is not necessarily a requirement for these new gauge bosons, it is essential to search in all decay modes. In particular, some models with extended weak or hypercharge gauge groups that offer an explanation for the high mass of the top quark predict that such bosons preferentially couple to third-generation fermions [7].

This Letter presents the first search for high-mass resonances decaying into $\tau^+\tau^-$ pairs using the ATLAS detector [8]. The Sequential Standard Model (SSM) is a benchmark model that contains a heavy neutral gauge boson, Z'_{SSM}, with the same couplings to fermions as the Z boson of the SM. This model is used to optimise the event selection of the search; limits on the cross section times $\tau^+\tau^-$ branching fraction of a generic neutral resonance are reported.

Direct searches for high-mass ditau resonances have been performed previously by the CDF [9] and CMS [10] collaborations. The latter search sets the most stringent 95% confidence level limits and excludes Z'_{SSM} masses below 1.4 TeV, with an expected limit of 1.1 TeV, using 4.9 fb^{-1} of integrated luminosity at $\sqrt{s} = 7$ TeV. Indirect limits on Z' bosons with non-universal flavour couplings have been set using measurements from LEP and LEP II [11] and translate to a lower bound on the Z' mass of 1.09 TeV. For comparison, the most stringent limits on Z'_{SSM} in the dielectron and dimuon decay channels combined are 2.2 TeV from ATLAS [12] and 2.3 TeV from CMS [13].

Tau leptons can decay into a charged lepton and two neutrinos ($\tau_{\mathrm{lep}} = \tau_e$ or τ_μ), or hadronically (τ_{had}), predominantly into one or three charged pions, a neutrino and often additional neutral pions. The $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ (branching ratio, BR = 42%), $\tau_\mu\tau_{\mathrm{had}}$ (BR = 23%), $\tau_e\tau_{\mathrm{had}}$ (BR = 23%) and $\tau_e\tau_\mu$ (BR = 6%) channels are analysed. Due to the different dominant background contributions and signal sensitivities, each channel is analysed separately and a statistical combination is used to maximise the sensitivity.

While the expected natural width of the Z'_{SSM} is small, approximately 3% of the Z' mass, the mass resolution is 30–50% in $\tau^+\tau^-$ decay modes due to the undetected neutrinos from the tau decays. Therefore, a counting experiment is performed in all analysis channels from events that pass a high-mass requirement.

2. Event samples

The data used in this search were recorded with the ATLAS detector in proton–proton (pp) collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV during the 2011 run of the Large Hadron Collider (LHC) [14]. The ATLAS detector consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer incorporating large superconducting toroid magnets. Each subdetector is divided into barrel and end-cap components.

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Only data taken with pp collisions in stable beam conditions and with all ATLAS subsystems operational are used, resulting in an integrated luminosity of 4.6 fb^{-1}. The data were collected using a combination of single-tau and ditau triggers, designed to select hadronic tau decays, and single-lepton triggers. The $\tau_{had}\tau_{had}$ channel uses events passing either a ditau trigger with transverse energy (E_T) thresholds of 20 and 29 GeV, or a single-tau trigger with an E_T threshold of 125 GeV. The $\tau_\mu\tau_{had}$ and $\tau_e\tau_\mu$ channels use events passing a single-muon trigger with a transverse momentum (p_T) threshold of 18 GeV, which is supplemented by accepting events that pass a single-muon trigger with a p_T threshold of 40 GeV that operates only in the barrel region but does not require a matching inner detector track. The $\tau_e\tau_{had}$ channel uses events passing a single-electron trigger with p_T thresholds in the range 20–22 GeV, depending on the data-taking period. Events that pass the trigger are selected if the vertex with the largest sum of the squared track momenta has at least four associated tracks, each with $p_T > 0.5$ GeV.

Monte Carlo (MC) simulation is used to estimate signal efficiencies and some background contributions. MC samples of background processes from W + jets and Z/γ^* + jets (enriched in high-mass $Z/\gamma^* \to \tau\tau$) events are generated with ALPGEN 2.13 [15], including up to five additional partons. Samples of $t\bar{t}$, Wt and diboson (WW, WZ, and ZZ) events are generated with MC@NLO 4.01 [16,17]. For these MC samples, the parton showering and hadronisation is performed by HERWIG 6.520 [18] interfaced to JIMMY 4.31 [19] for multiple parton interactions. Samples of s-channel and t-channel single top-quark production are generated with AcerMC 3.8 [20], with the parton showering and hadronisation performed by PYTHIA 6.425 [21]. Samples of Z'_{SSM} signal events are generated with PYTHIA 6.425, for eleven mass hypotheses ranging from 500 to 1750 GeV in steps of 125 GeV. In all samples photon radiation is performed by PHOTOS [22], and tau lepton decays are generated with TAUOLA [23]. The choice of parton distribution functions (PDFs) depends on the generator: CTEQ6L1 [24] is used with ALPGEN, CT10 [25] with MC@NLO and MRST2007 LO* [26] with PYTHIA and AcerMC.

The Z/γ^* cross section calculated at next-to-next-to-leading order (NNLO) using PHOZPR [27] with MSTW2008 PDFs [28] is used to derive mass-dependent K-factors that are applied to the leading order Z/γ^* + jets and $Z' \to \tau\tau$ cross sections. The W + jets cross section is calculated at NNLO using FEWZ 2.0 [29,30]. The $t\bar{t}$ cross section is calculated at approximate NNLO [31–33]. The cross sections for single-top production are calculated at next-to-next-to-leading logarithm for the s-channel [34] and approximate NNLO for t-channel and Wt production modes [35].

The detector response for each MC sample is simulated using a detailed GEANT4 [36] model of the ATLAS detector and subdetector-specific digitisation algorithms [37]. As the data are affected by the detector response to multiple pp interactions occurring in the same or in neighbouring bunch crossings (referred to as pile-up), minimum-bias interactions generated with PYTHIA 6.425 (with a specific LHC tune [38]) are overlaid on the generated signal and background events. The resulting events are re-weighted so that the distribution of the number of minimum-bias interactions per bunch crossing agrees with data. All samples are simulated with more than twice the effective luminosity of the data, except W + jets, where an equivalent of approximately 1.5 fb^{-1} is simulated.

3. Physics object reconstruction

Muon candidates are reconstructed by combining an inner detector track with a track from the muon spectrometer. They are required to have $p_T > 10$ GeV and $|\eta| < 2.5$.[1] Muon quality criteria are applied in order to achieve a precise measurement of the muon momentum and reduce the misidentification rate [39]. These quality requirements correspond to a muon reconstruction and identification efficiency of approximately 95%.

Electrons are reconstructed by matching clustered energy deposits in the EM calorimeter to tracks reconstructed in the inner detector [40]. The electron candidates are required to have $p_T > 15$ GeV and to be within the fiducial volume of the inner detector, $|\eta| < 2.47$. The transition region between the barrel and end-cap EM calorimeters, with $1.37 < |\eta| < 1.52$, is excluded. The candidates are required to pass quality criteria based on the expected calorimeter shower shape and amount of radiation in the transition radiation tracker. These quality requirements correspond to an electron identification (ID) efficiency of approximately 90%. Electrons and muons are considered isolated if they are away from large deposits of energy in the calorimeter, or tracks with large p_T consistent with originating from the same vertex.[2] In the $\tau_e\tau_{had}$ channel, isolated electrons are also required to pass a tighter identification requirement corresponding to an efficiency of approximately 80%.

Jets are reconstructed using the anti-k_t algorithm [41,42] with a radius parameter value of 0.4. The algorithm uses reconstructed, noise-suppressed clusters of calorimeter cells [43]. Jets are calibrated to the hadronic energy scale with correction factors based on simulation and validated using test-beam and collision data [44]. All jets are required to have $p_T > 25$ GeV and $|\eta| < 4.5$. For jets within the inner detector acceptance ($|\eta| < 2.4$), the *jet vertex fraction* is required to be at least 0.75; the jet vertex fraction is defined as the sum of the p_T of tracks associated with the jet and consistent with originating from the selected primary vertex, divided by the sum of the p_T of all tracks associated with the jet. This requirement reduces the number of jets that originate from pile-up or are heavily contaminated by it. Events are discarded if a jet is associated with out-of-time activity or calorimeter noise [45].

Candidates for hadronic tau decays are defined as jets with either one or three associated tracks reconstructed in the inner detector. The kinematic properties of the tau candidate are reconstructed from the *visible* tau lepton decay products (all products excluding neutrinos). The tau charge is reconstructed from the sum of the charges of the associated tracks and is required to be ±1. The charge misidentification probability is found to be negligible. Hadronic tau decays are identified with a multivariate algorithm that employs boosted decision trees (BDTs) to discriminate against quark- and gluon-initiated jets using shower shape and tracking information [46]. Working points with a tau identification efficiency of about 50% (*medium*) for the $\tau_\mu\tau_{had}$ and $\tau_e\tau_{had}$ channels and 60% (*loose*) for the $\tau_{had}\tau_{had}$ channel are chosen, leading to a rate of false identification for quark- and gluon-initiated jets of a few percent [47]. Tau candidates are also required to have $p_T > 35$ GeV and to be in the fiducial volume of the inner detector, $|\eta| < 2.47$

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Separation in the η–ϕ plane is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

[2] Lepton isolation is defined using the sum of the E_T deposited in calorimeter cells within $\Delta R < 0.2$ of the lepton, $E_T^{0.2}$, and the scalar sum of the p_T of tracks with $p_T > 0.5$ GeV consistent with the same vertex as the lepton and within $\Delta R < 0.4$, $p_T^{0.4}$. Muons are considered isolated if they have $E_T^{0.2}/p_T < 4\%$ (and $p_T^{0.4}/p_T < 6\%$ in the $\tau_e\tau_\mu$ channel). Isolated electrons must have $p_T^{0.4}/p_T < 5\%$ and $E_T^{0.2}/p_T < 5\%$ if $p_T < 100$ GeV or $E_T^{0.2} < 5$ GeV otherwise ($E_T^{0.2}/p_T < 6\%$ and $p_T^{0.4}/p_T < 8\%$ in the $\tau_e\tau_\mu$ channel).

(the EM calorimeter transition region is excluded). In the $\tau_{\text{lep}}\tau_{\text{had}}$ channels, tau candidates are required to have only one track, which must not be in the range $|\eta| < 0.05$, and to pass a muon veto. The removed pseudorapidity region corresponds to a gap in the transition radiation tracker that reduces the power of electron/pion discrimination. In the $\tau_e\tau_{\text{had}}$ channel, tau candidates are also required to pass an electron veto using BDTs.

Geometric overlap of objects with $\Delta R < 0.2$ is resolved by selecting only one of the overlapping objects in the following order of priority: muons, electrons, tau candidates and jets. The missing transverse momentum (with magnitude $E_{\text{T}}^{\text{miss}}$) is calculated from the vector sum of the transverse momenta of all high-p_{T} objects reconstructed in the event, as well as a term for the remaining activity in the calorimeter [48]. Clusters associated with electrons, hadronic tau decays and jets are calibrated separately, with the remaining clusters calibrated at the EM energy scale.

4. Event selection

Selected events in the $\tau_{\text{had}}\tau_{\text{had}}$ channel must contain at least two oppositely-charged tau candidates with $p_{\text{T}} > 50$ GeV and no electrons with $p_{\text{T}} > 15$ GeV or muons with $p_{\text{T}} > 10$ GeV. If the event was selected by the ditau trigger, both tau candidates are required to be geometrically matched to the objects that passed the trigger. For events that pass only the single-tau trigger there is no ambiguity, so trigger matching is not required. If multiple tau candidates are selected, the two highest-p_{T} candidates are chosen. The angle between the tau candidates in the transverse plane must be greater than 2.7 radians.

Selected events in the $\tau_{\text{lep}}\tau_{\text{had}}$ channels must contain exactly one isolated muon with $p_{\text{T}} > 25$ GeV or an isolated electron with $p_{\text{T}} > 30$ GeV; no additional electrons with $p_{\text{T}} > 15$ GeV or muons with $p_{\text{T}} > 4$ GeV; and exactly one tau candidate with $p_{\text{T}} > 35$ GeV. The angle between the lepton and tau candidate in the transverse plane must be greater than 2.7 radians, and the pair must have opposite electric charge.

For the $\tau_e\tau_{\text{had}}$ channel, the $Z \to ee$ and multijet contributions are reduced to a negligible level by requiring $E_{\text{T}}^{\text{miss}} > 30$ GeV. The W + jets background is suppressed by requiring the transverse mass, m_{T}, of the electron–$E_{\text{T}}^{\text{miss}}$ system, defined as

$$m_{\text{T}} = \sqrt{2 p_{\text{T}e} E_{\text{T}}^{\text{miss}} (1 - \cos\Delta\phi)}, \tag{1}$$

where $\Delta\phi$ is the angle between the lepton and $E_{\text{T}}^{\text{miss}}$ in the transverse plane, to be less than 50 GeV.

Selected events in the $\tau_e\tau_\mu$ channel must contain exactly one isolated muon with $p_{\text{T}} > 25$ GeV and one isolated electron with $p_{\text{T}} > 35$ GeV and opposite electric charge, no additional electrons with $p_{\text{T}} > 15$ GeV or muons with $p_{\text{T}} > 10$ GeV and not more than one jet. The jet requirement suppresses $t\bar{t}$ events, which typically have higher jet multiplicity than the signal. The two leptons are required to be back-to-back in the transverse plane using the criterion $p_\zeta^{\text{vis}} < 10$ GeV, with

$$p_\zeta^{\text{vis}} = \vec{p}_{\text{T}e} \cdot \hat{\zeta} + \vec{p}_{\text{T}\mu} \cdot \hat{\zeta}, \tag{2}$$

where $\hat{\zeta}$ is a unit vector along the bisector of the e and μ momenta. This selection provides good suppression of the diboson and $t\bar{t}$ backgrounds. For Z' events, the $E_{\text{T}}^{\text{miss}}$ tends to point away from the highest-p_{T} lepton, so the angle between the highest-p_{T} lepton and $E_{\text{T}}^{\text{miss}}$ in the transverse plane is required to be greater than 2.6 radians.

The search in all channels is performed by counting events in signal regions with *total transverse mass* above thresholds optimised separately for each signal mass hypothesis in each channel to give the best expected exclusion limits (see Table 1). The total transverse mass, $m_{\text{T}}^{\text{tot}}$, is defined as the mass of the visible decay products of both tau leptons and $E_{\text{T}}^{\text{miss}}$, neglecting longitudinal momentum components and the tau lepton mass,

$$m_{\text{T}}^{\text{tot}} = \sqrt{2 p_{\text{T}1} p_{\text{T}2} C + 2 E_{\text{T}}^{\text{miss}} p_{\text{T}1} C_1 + 2 E_{\text{T}}^{\text{miss}} p_{\text{T}2} C_2}, \tag{3}$$

where $p_{\text{T}1}$ and $p_{\text{T}2}$ are the transverse momenta of the visible products of the two tau decays; C is defined as $1 - \cos\Delta\phi$, where $\Delta\phi$ is the angle in the transverse plane between the visible products of the two tau decays; and C_1 and C_2 are defined analogously for the angles in the transverse plane between $E_{\text{T}}^{\text{miss}}$ and the visible products of the first and second tau decay, respectively. Figs. 1(a)–1(d) show the $m_{\text{T}}^{\text{tot}}$ distribution after event selection in each channel.

Table 1
Thresholds on $m_{\text{T}}^{\text{tot}}$ used for each signal mass point in each channel. All values are given in GeV.

$m_{Z'}$	500	625	750	875	1000	1125	$\geqslant 1250$
$\tau_{\text{had}}\tau_{\text{had}}$	350	400	500	500	650	650	700
$\tau_\mu\tau_{\text{had}}$	400	400	500	500	600	600	600
$\tau_e\tau_{\text{had}}$	400	400	400	500	500	500	500
$\tau_e\tau_\mu$	300	350	350	350	500	500	500

5. Background estimation

The dominant background processes in the $\tau_{\text{had}}\tau_{\text{had}}$ channel are multijet production and $Z/\gamma^* \to \tau\tau$. Minor contributions come from $W(\to \tau\nu)$+jets, $Z(\to \ell\ell)$+jets ($\ell = e$ or μ), $W(\to \ell\nu)$+jets, $t\bar{t}$, single top-quark and diboson production. The shape of the multijet mass distribution is estimated from data that pass the full event selection but have two tau candidates of the same electric charge. The contribution is normalised to events that pass the full event selection but have low $m_{\text{T}}^{\text{tot}}$. All other background contributions are estimated from simulation.

The main background contributions in the $\tau_{\text{lep}}\tau_{\text{had}}$ channels come from $Z/\gamma^* \to \tau\tau$, W + jets, $t\bar{t}$ and diboson production, with minor contributions from $Z(\to \ell\ell)$ + jets, multijet and single top-quark events. The contributions involving fake hadronic tau decays from multijet and W + jets events are modelled with data-driven techniques involving *fake factors*, which parameterise the rate for lepton candidates in jets to pass lepton isolation or jets to pass tau identification, respectively. The remaining background is estimated using simulation.

The dominant background processes in the $\tau_e\tau_\mu$ channel are $t\bar{t}$, $Z/\gamma^* \to \tau\tau$ and diboson production. Contributions from processes such as $Z(\to \mu\mu)$ + jets, W + jets and $W\gamma$ + jets, where a jet or photon is misidentified as an electron, are very small in the signal region. Multijet events are suppressed by tight lepton isolation criteria. Since background processes involving fake leptons make only minor contributions, all background contributions in the $\tau_e\tau_\mu$ channel are estimated using simulation. The MC estimates of the dominant background contributions are checked using high-purity control regions in data.

The following subsections describe the data-driven background estimates in more detail.

5.1. Multijet background in the $\tau_{\text{had}}\tau_{\text{had}}$ channel

The shape of the $m_{\text{T}}^{\text{tot}}$ distribution for the multijet background is estimated using events that pass the standard event selection, but have two selected τ_{had} candidates with the same electric charge and with $m_{\text{T}}^{\text{tot}} > 200$ GeV to avoid the low $m_{\text{T}}^{\text{tot}}$ region which is affected by the tau p_{T} threshold. For a low-mass signal with $m_{Z'} \leqslant 625$ GeV, a lower bound of 160 GeV is used, as

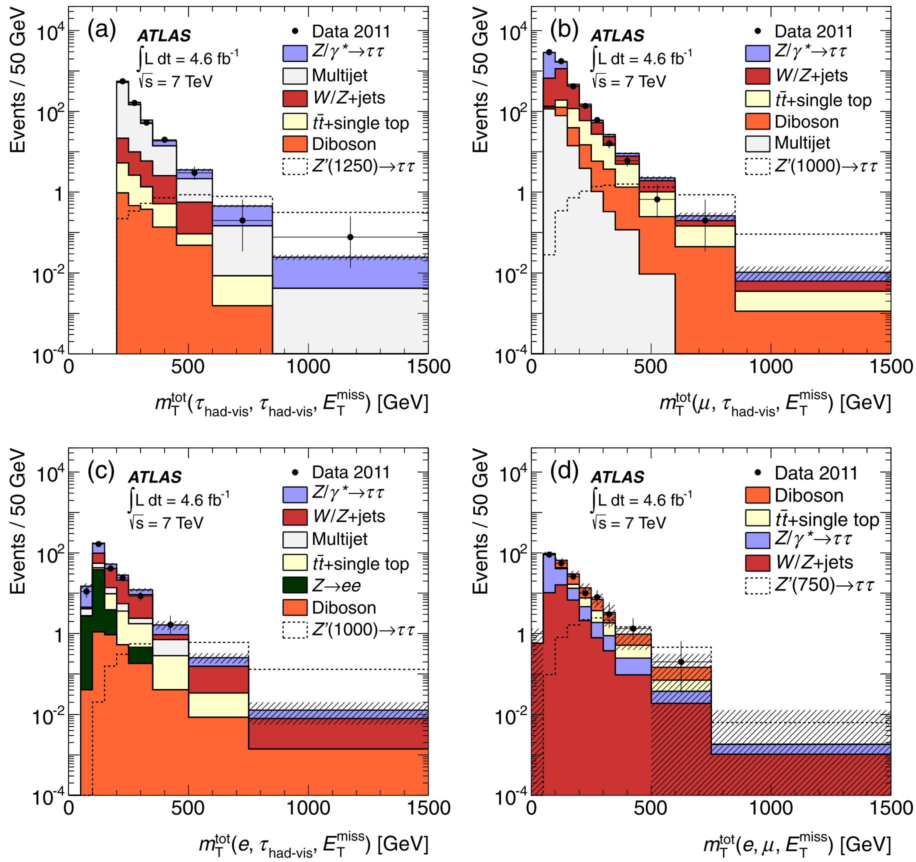

Fig. 1. The $m_{\mathrm{T}}^{\mathrm{tot}}$ distribution after event selection without the $m_{\mathrm{T}}^{\mathrm{tot}}$ requirement for each channel: (a) $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$, (b) $\tau_{\mu}\tau_{\mathrm{had}}$, (c) $\tau_{e}\tau_{\mathrm{had}}$ and (d) $\tau_{e}\tau_{\mu}$. The estimated contributions from SM processes are stacked and appear in the same order as in the legend. The contribution from $Z \to ee$ events in which an electron is misidentified as a tau candidate is shown separately in the $\tau_{e}\tau_{\mathrm{had}}$ channel. A Z'_{SSM} signal and the events observed in data are overlaid. The signal mass point closest to the Z'_{SSM} exclusion limit in each channel is chosen and is indicated in parentheses in the legend in units of GeV. The uncertainty on the total estimated background (hatched) includes only the statistical uncertainty from the simulated samples. The visible decay products of hadronically decaying taus are denoted by $\tau_{\mathrm{had\text{-}vis}}$.

discussed below. This control region has only 2% contamination from other background processes and negligible signal contamination. The $m_{\mathrm{T}}^{\mathrm{tot}}$ distribution is modelled by performing an unbinned maximum likelihood fit to the data in the control region using the following function:

$$f\left(m_{\mathrm{T}}^{\mathrm{tot}}\middle|p_0, p_1, p_2\right) = p_0 \cdot \left(m_{\mathrm{T}}^{\mathrm{tot}}\right)^{p_1 + p_2 \log(m_{\mathrm{T}}^{\mathrm{tot}})}, \quad (4)$$

where p_0, p_1 and p_2 are free parameters. The integral of the fitted function in the high-mass tail matches the number of observed events well for any choice of the $m_{\mathrm{T}}^{\mathrm{tot}}$ threshold, and the function models the high-mass tail well in a simulated dijet sample enriched in high-mass events. The statistical uncertainty is estimated using pseudo-experiments and increases monotonically from 12% to 83% with increasing $m_{\mathrm{T}}^{\mathrm{tot}}$ threshold. The systematic uncertainty due to the choice of the fitting function is evaluated using alternative fitting functions and ranges from 1% to 7%. The multijet model is normalised to data that pass all analysis requirements but have $m_{\mathrm{T}}^{\mathrm{tot}}$ in the range 200–250 GeV. For the low-mass points with $m_{Z'} \leqslant 625$ GeV, the low-$m_{\mathrm{T}}^{\mathrm{tot}}$ side-band is lowered to 160–200 GeV to keep signal contamination negligible. Both side-bands have a maximum contamination of 5% from other background processes, which is subtracted, and negligible contamination from signal. The statistical uncertainty from the normalisation ranges from 2% to 5%. Systematic uncertainties affecting the normalisation of the background processes are propagated when performing the subtraction but have a negligible effect.

5.2. Multijet background in the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channels

The background from multijet events is negligible at high $m_{\mathrm{T}}^{\mathrm{tot}}$, but it is important to estimate its contribution to model the inclusive mass distribution. Multijet events are exceptional among the background processes because the muons and electrons produced in heavy-flavour decays or the light-flavour hadrons falsely identified as electrons, are typically not isolated in the calorimeter but produced in jets. To estimate the multijet background, events in the data that fail lepton isolation are weighted event-by-event, with fake factors for lepton isolation measured from data in a multijet-rich control region (multijet-CR). The multijet-CR is defined by requiring exactly one selected lepton, as in Section 4, but without the isolation requirement; at least one tau candidate that fails the BDT ID; no tau candidates that pass the BDT ID; $E_{\mathrm{T}}^{\mathrm{miss}} < 15$ GeV for the $\tau_{\mu}\tau_{\mathrm{had}}$ channel, $E_{\mathrm{T}}^{\mathrm{miss}} < 30$ GeV for the $\tau_{e}\tau_{\mathrm{had}}$ channel; and the transverse mass formed by the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$, to be less than 30 GeV. For the $\tau_{\mu}\tau_{\mathrm{had}}$ channel, where the multijet contribution is dominated by b-quark-initiated jets, the muon is additionally required to have a transverse impact parameter of $|d_0(\mu)| > 0.08$ mm with respect to the primary vertex, which increases the purity of the multijet control region. The leptons in the multijet control region are divided into those that pass (isolated) and a subset that fail (anti-isolated) the isolation requirements. In the $\tau_{\mu}\tau_{\mathrm{had}}$ channel the anti-isolated sample includes all muons that fail isolation, while in the $\tau_{e}\tau_{\mathrm{had}}$ channel, the anti-isolation requirement is tightened to reduce contamination from real isolated electrons. Isolation fake factors, f_{iso}, are defined as the number of isolated leptons in the data, N^{iso}, divided by the number of anti-isolated leptons, $N^{\text{anti-iso}}$, binned in p_{T} and η:

$$f_{\text{iso}}(p_{\text{T}},\eta) \equiv \left.\frac{N^{\text{iso}}(p_{\text{T}},\eta)}{N^{\text{anti-iso}}(p_{\text{T}},\eta)}\right|_{\text{multijet-CR}}. \quad (5)$$

Contamination from real isolated leptons is estimated using simulation and subtracted from N^{iso} ($\sim$3% for $\tau_\mu\tau_{\text{had}}$ and $\sim$25% for $\tau_e\tau_{\text{had}}$). The number of multijet events passing lepton isolation, N_{multijet}, is predicted by weighting the events with anti-isolated leptons by their fake factor:

$$N_{\text{multijet}}(p_{\text{T}},\eta,x) = f_{\text{iso}}(p_{\text{T}},\eta)\big(N^{\text{anti-iso}}_{\text{data}}(p_{\text{T}},\eta,x) - N^{\text{anti-iso}}_{\text{MC}}(p_{\text{T}},\eta,x)\big). \quad (6)$$

The shape of the multijet background in a given kinematic variable, x, is modelled from the events in the data with anti-isolated leptons, $N^{\text{anti-iso}}_{\text{data}}$, corrected by subtracting the expected contamination from other background processes predicted with MC simulation, $N^{\text{anti-iso}}_{\text{MC}}$.

This method assumes that the ratio of the number of isolated leptons to the number of anti-isolated leptons in multijet events is not strongly correlated with the requirements used to enrich the multijet control sample. This assumption has been verified by varying the $E_{\text{T}}^{\text{miss}}$ and d_0 selection criteria used to define the multijet control region. A conservative 100% systematic uncertainty on the isolation fake factor is assumed, but this has negligible effect on the sensitivity because the expected multijet background is less than a percent of the total background in both the $\tau_\mu\tau_{\text{had}}$ and $\tau_e\tau_{\text{had}}$ channels.

5.3. W + jets background in the $\tau_{\text{lep}}\tau_{\text{had}}$ channels

The W + jets background is estimated using a technique similar to the multijet estimate, where tau candidates that fail the BDT ID are weighted event-by-event with fake factors for jets to pass the BDT ID in W + jets events. A high purity W + jets control region (W-CR) is defined by selecting events that have exactly one isolated lepton, as in Section 4; at least one tau candidate that is not required to pass the BDT ID; and $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}})$ between 70 and 200 GeV. For the $\tau_e\tau_{\text{had}}$ channel, the tau candidate is additionally required to pass the electron veto. Tau ID fake factors, f_τ, are defined as the number of tau candidates that pass the BDT ID, $N^{\text{pass }\tau\text{-ID}}$, divided by the number that fail, $N^{\text{fail }\tau\text{-ID}}$, binned in p_{T} and η:

$$f_\tau(p_{\text{T}},\eta) \equiv \left.\frac{N^{\text{pass }\tau\text{-ID}}(p_{\text{T}},\eta)}{N^{\text{fail }\tau\text{-ID}}(p_{\text{T}},\eta)}\right|_{\text{W-CR}}. \quad (7)$$

The number of W + jets events passing the BDT ID, $N_{W+\text{jets}}$, is predicted by weighting the events that fail the BDT ID by their fake factor:

$$N_{W+\text{jets}}(p_{\text{T}},\eta,x) = f_\tau(p_{\text{T}},\eta)\big(N^{\text{fail }\tau\text{-ID}}_{\text{data}}(p_{\text{T}},\eta,x) - N^{\text{fail }\tau\text{-ID}}_{\text{multijet}}(p_{\text{T}},\eta,x) - N^{\text{fail }\tau\text{-ID}}_{\text{MC}}(p_{\text{T}},\eta,x)\big). \quad (8)$$

The shape of the W + jets background is modelled using events in the data that failed the BDT ID, $N^{\text{fail }\tau\text{-ID}}_{\text{data}}$, with the multijet contamination, $N^{\text{fail }\tau\text{-ID}}_{\text{multijet}}$ (estimated from data), and other contamination, $N^{\text{fail }\tau\text{-ID}}_{\text{MC}}$ (estimated from simulation), subtracted.

A 30% systematic uncertainty on the fake factors is assigned by comparing the fake factors to those measured in a data sample enriched in Z + jets instead of W + jets, which provides a sample of jets with a similar quark/gluon fraction [49]. This background estimation method relies on the assumption that the tau identification fake factors for W + jets events are not strongly correlated with the selection used to define the W + jets control region. This assumption has been verified by varying the m_{T} selection criterion used to define the W + jets control region, resulting in a few percent variation, which is well within the systematic uncertainty.

6. Systematic uncertainties

Systematic effects on the contributions of signal and background processes estimated from simulation are discussed in this section. These include theoretical uncertainties on the cross sections of simulated processes and experimental uncertainties on the trigger, reconstruction and identification efficiencies; on the energy and momentum scales and resolutions; and on the measurement of the integrated luminosity. For each source of uncertainty, the correlations across analysis channels, as well as the correlations between signal and background, are taken into account. Uncertainties on the background contributions estimated from data have been discussed in their respective sections.

The overall uncertainty on the Z' signal and the $Z/\gamma^* \to \tau\tau$ background due to PDFs, α_S and scale variations is estimated to be 12% at 1.5 TeV, dominated by the PDF uncertainty [12]. The uncertainty is evaluated using PDF error sets, and the spread of the variations covers the difference between the central values obtained with the CTEQ and MSTW PDF sets. Additionally, for $Z/\gamma^* \to \tau\tau$, a systematic uncertainty of 10% is attributed to electroweak corrections [50]. This uncertainty is not considered for the signal as it is strongly model-dependent. An uncertainty of 4–5% is assumed for the inclusive cross section of the single gauge boson and diboson production mechanisms and a relative uncertainty of 24% is added in quadrature per additional jet, due to the irreducible Berends-scaling uncertainty [51,52]. For $t\bar{t}$ and single top-quark production, the QCD scale uncertainties are in the range of 3–6% [35,53,54]. The uncertainties related to the proton PDFs, including those arising from the choice of PDF set, amount to 8% for the predominantly gluon-initiated processes such as $t\bar{t}$ and 4% for the predominantly quark-initiated processes at low mass, such as on-shell single gauge boson and diboson production [25,28,55–57].

The uncertainty on the integrated luminosity is 3.9% [58,59]. The efficiencies of the electron, muon and hadronic tau triggers are measured in data and are used to correct the simulation. The associated systematic uncertainties are typically 1–2% for electrons and muons, 2.5% for the ditau trigger and 5% for the high-p_{T} single-tau trigger. Differences between data and simulation in the reconstruction and identification efficiencies of electrons, muons, and hadronic tau decays are taken into account, as well as the differences in the energy and momentum scales and resolutions. The associated uncertainties for muons and electrons are typically < 1%.

The systematic uncertainties on the identification efficiency of hadronic tau decays are estimated at low p_{T} from data samples enriched in $W \to \tau\nu$ and $Z \to \tau\tau$ events. At high p_{T}, there are no abundant sources of real hadronic tau decays to make an efficiency measurement. Rather, the fraction of jets that pass the tau identification is studied in high-p_{T} dijet events as a function of the jet p_{T}, which indicates that there is no degradation in the modelling of the detector response as a function of the p_{T} of tau candidates. From these studies, an efficiency uncertainty of up to 8% is assigned to high-p_{T} tau candidates. The uncertainty on the jet-to-tau misidentification rate is 50%, determined from data-MC comparisons in W + jet events. The uncertainty on the electron-to-tau misidentification rate is 50–100%, depending on the pseudorapidity of the tau candidate, based on measurements made using a $Z \to ee$ sample selected from data [47]. The energy scale uncertainty on taus and jets is evaluated based on the single-hadron response in

Table 2
Uncertainties on the estimated signal and total background contributions in percent for each channel. The following signal masses, chosen to be close to the region where the limits are set, are used: 1250 GeV for $\tau_{had}\tau_{had}$ (hh); 1000 GeV for $\tau_\mu\tau_{had}$ (μh) and $\tau_e\tau_{had}$ (eh); and 750 GeV for $\tau_e\tau_\mu$ ($e\mu$). A dash denotes that the uncertainty is not applicable. The statistical uncertainty corresponds to the uncertainty due to limited sample size in the MC and control regions.

Uncertainty [%]	Signal				Background			
	hh	μh	eh	$e\mu$	hh	μh	eh	$e\mu$
Stat. uncertainty	1	2	2	3	5	20	23	7
Eff. and fake rate	16	10	8	1	12	16	4	3
Energy scale and res.	5	7	6	2	$^{+22}_{-11}$	3	8	5
Theory cross section	8	6	6	5	9	4	4	5
Luminosity	4	4	4	4	2	2	2	4
Data-driven methods	–	–	–	–	$^{+21}_{-11}$	6	16	–

the calorimeters [44,60]. In addition, the tau energy scale is validated in data samples enriched in $Z \to \tau\tau$ events. The systematic uncertainties related to the jet and tau energy scale and resolution are functions of η and p_T, and are generally near 3%. These uncertainties are treated as fully correlated. Energy scale and resolution uncertainties on all objects are propagated to the E_T^{miss} calculation. The uncertainty on the E_T^{miss} due to clusters that do not belong to any reconstructed object is measured to be negligible in all channels.

Table 2 summarises the uncertainties on the estimated signal and total background contributions in each channel. For the background, the contribution from each uncertainty depends on the fraction of the background estimated with simulation. The dominant uncertainties on the background come from the multijet shape estimation and the tau energy scale uncertainty for $Z/\gamma^* \to \tau\tau$ events in the $\tau_{had}\tau_{had}$ channel, from the limited sample size and the fake factor estimate of the W + jets background in the $\tau_{lep}\tau_{had}$ channels and from the statistical uncertainty of the MC samples in the $\tau_e\tau_\mu$ channel. The dominant uncertainty on the signal for the $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels comes from the tau identification efficiency and for the $\tau_e\tau_\mu$ channel, from the statistical uncertainty on the MC samples.

7. Results and discussion

The numbers of observed and expected events including their total uncertainties, after the full selection in all channels, are summarised in Table 3. In all cases, the number of observed events is consistent with the expected Standard Model background. Therefore, upper limits are set on the production of a high-mass resonance decaying to $\tau^+\tau^-$ pairs.

The statistical combination of the channels employs a likelihood function constructed as the product of Poisson probability terms describing the total number of events observed in each channel. The Poisson probability in each channel is evaluated for the observed number of data events given the signal plus background expectation. Systematic uncertainties on the expected number of events are incorporated into the likelihood via Gaussian-distributed nuisance parameters. Correlations across channels are taken into account. A signal strength parameter multiplies the expected signal in each channel, for which a positive uniform prior probability distribution is assumed. Theoretical uncertainties on the signal cross section are not included in the calculation of the experimental limit as they are model-dependent.

Bayesian 95% credibility upper limits are set on the cross section times branching fraction for a high-mass resonance decaying into a $\tau^+\tau^-$ pair as a function of the resonance mass, using the Bayesian Analysis Toolkit [61]. Figs. 2(a) and 2(b) show the limits for the individual channels and for the combination, respectively. The resulting 95% credibility lower limit on the mass of a Z'_{SSM} decaying to $\tau^+\tau^-$ pairs is 1.40 TeV, with an expected limit of 1.42 TeV. The observed and expected limits in the individual channels are, respectively: 1.26 and 1.35 TeV ($\tau_{had}\tau_{had}$); 1.07 and 1.06 TeV ($\tau_\mu\tau_{had}$); 1.10 and 1.03 TeV ($\tau_e\tau_{had}$); and 0.72 and 0.82 TeV ($\tau_e\tau_\mu$).

The impact of the choice of the prior on the signal strength parameter has been evaluated by also considering the reference prior [62]. Use of the reference prior improves the mass limits by approximately 50 GeV. The impact of the vector and axial coupling strengths of the Z' has been investigated, as these can alter the fraction of the tau momentum carried by the visible decay products. For purely $V - A$ couplings, the limit on the cross section times $\tau^+\tau^-$ branching fraction is improved by ∼10% over the mass range. For purely $V + A$ couplings, there is a mass-dependent degradation, from ∼15% at high mass to ∼40% at low mass. All variations lie within the 1σ band of the expected exclusion limit.

8. Conclusion

A search for high-mass ditau resonances has been performed using 4.6 fb^{-1} of data collected with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV at the LHC. The $\tau_{had}\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$ and $\tau_e\tau_\mu$ channels are analysed. The observed number of events in the high-transverse-mass region is consistent with the SM expec-

Table 3
Number of expected and observed events after event selection for each analysis channel. The expected contribution from the signal and background in each channel is calculated for the signal mass point closest to the Z'_{SSM} exclusion limit. The total uncertainties on each estimated contribution are shown. The signal efficiency denotes the expected number of signal events divided by the product of the production cross section, the ditau branching fraction and the integrated luminosity, $\sigma(pp \to Z'_{SSM}) \times \mathrm{BR}(Z'_{SSM} \to \tau\tau) \times \int L\,dt$.

	$\tau_{had}\tau_{had}$	$\tau_\mu\tau_{had}$	$\tau_e\tau_{had}$	$\tau_e\tau_\mu$
$m_{Z'}$ [GeV]	1250	1000	1000	750
m_T^{tot} threshold [GeV]	700	600	500	350
$Z/\gamma^* \to \tau\tau$	0.73 ± 0.23	0.36 ± 0.06	0.57 ± 0.11	0.55 ± 0.07
W + jets	< 0.03	0.28 ± 0.22	0.8 ± 0.4	0.33 ± 0.10
$Z(\to \ell\ell)$ + jets	< 0.01	< 0.1	< 0.01	0.06 ± 0.02
$t\bar{t}$	< 0.02	0.33 ± 0.15	0.13 ± 0.09	0.97 ± 0.22
Diboson	< 0.01	0.23 ± 0.07	0.06 ± 0.03	1.69 ± 0.24
Single top	< 0.01	0.19 ± 0.18	< 0.1	< 0.1
Multijet	0.24 ± 0.15	< 0.01	< 0.1	< 0.01
Total expected background	0.97 ± 0.27	1.4 ± 0.4	1.6 ± 0.5	3.6 ± 0.4
Events observed	2	1	0	5
Expected signal events	6.3 ± 1.1	5.5 ± 0.7	5.0 ± 0.5	6.72 ± 0.26
Signal efficiency (%)	4.3	1.1	1.0	0.4

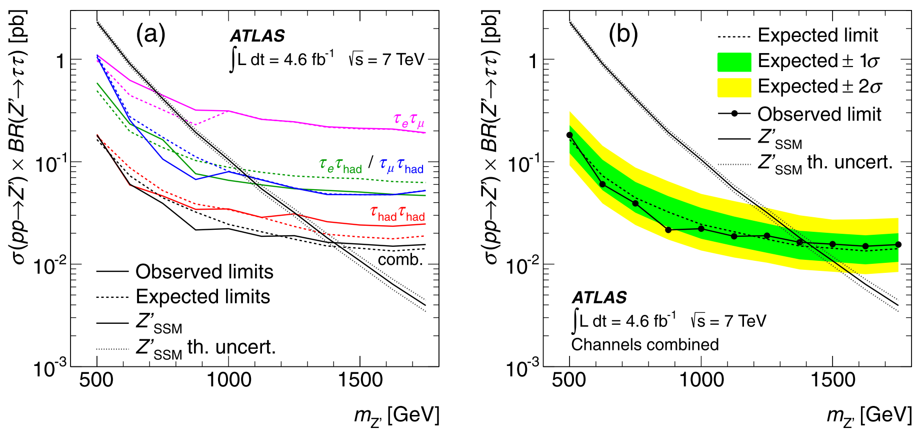

Fig. 2. (a) The expected (dashed) and observed (solid) 95% credibility upper limits on the cross section times $\tau^+\tau^-$ branching fraction, in the $\tau_{had}\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$ and $\tau_e\tau_\mu$ channels and for the combination. The expected Z'_{SSM} production cross section and its corresponding theoretical uncertainty (dotted) are also included. (b) The expected and observed limits for the combination including 1σ and 2σ uncertainty bands. Z'_{SSM} masses up to 1.40 TeV are excluded, in agreement with the expected limit of 1.42 TeV in the absence of a signal.

tation. Limits are set on the cross section times branching fraction for such resonances. The resulting lower limit on the mass of a Z' decaying to $\tau^+\tau^-$ in the Sequential Standard Model is 1.40 TeV at 95% credibility, in agreement with the expected limit of 1.42 TeV in the absence of a signal.

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